# INVESTIGATIONS ABOUT METHODS TO CONTROL AIRFLOW IN ROAD TUNNELS

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## ABSTRACT

For road tunnels with and without smoke extraction, the control of longitudinal airflow is essential in order to limit smoke propagation in case of fire.

Various concepts for the handling of longitudinal airflow have been investigated. These include jet fans, the use of (semi-)transverse ventilation, directed point air injection (Saccardo-nozzles), local air extraction, air curtains and mechanical curtains.

At present, the application of jet fans is the standard solution, but not necessarily the optimum for all applications.

Jet fan installation in the traffic envelope often leads to problems with corrosion and accessibility for maintenance and repair. Jet fans require extra space under the ceiling or in niches. This may lead to high additional costs if jet fans have to be retrofitted during ventilation system upgrades in existing tunnels.

Particular attention is paid to the rededication of existing supply air ducts in tunnels with transverse ventilation systems. Many tunnels of medium lengths were equipped with this kind of system when vehicle emissions were very high and the need to control the longitudinal airflow was secondary. In many of these tunnels, the distributed air extraction is going to be abolished during a safety upgrade and replaced by concentrated smoke extraction through remote controlled dampers. Distributed supply air is no longer needed because for mechanical ventilation in normal operation, concentrated extraction or longitudinal ventilation can be applied.

As these supply air ducts are connected to functioning ventilation stations a new use for them suggests itself which could be an economic application of control of the longitudinal air flow in case of tunnel fires. This leads to the concept of directed point air injection, which is one of the main focuses in this investigation.

Many descriptions of simulations, small-scale tests and real tunnel applications are found in the available literature. The one-dimensional calculation method by application of the energy equation and the balance of momentum is well established and very similar to that used for the design of jet fan applications.

Nevertheless, some decisive parameters are uncertain and depend on the actual layout. To reduce the uncertainties, a series of tests has been performed with a full scale model of a Saccardo nozzle in an existing road tunnel.

The results of the measurements and simulations are in close agreement to the assumptions applied. They enhance the knowledge about the decisive parameters. Limits for the application of point air injection have been identified.

*Keywords: Aerodynamics, retrofit, tunnel fire, smoke extraction, ventilation, measurements.*

## 1. CONTROL OF AIRFLOW IN CASE OF FIRE

Immediately after the start of a tunnel fire, the smoke spreads along with the existing airflow in the tunnel.

When using a smoke extraction system, the paramount goal of the fire ventilation is to support the escape of tunnel users by confining the spread of smoke to a limited space. Without effective control of the airflow, this may fail.

Effects acting on the airflow in the tunnel are:

- Traffic, dying away after the start of the fire
- Mechanical ventilation in normal operation, shut down automatically
- Wind on portals, of unknown magnitude
- Barometric pressure differences between portals, of unknown magnitude
- Buoyancy due to temperature differences between tunnel and vicinity, varying
- Buoyancy due to fire heat, possibly increasing
- Inertia of the air column in the tunnel

## 2. CLASSIFICATION OF AIRFLOW CONTROL METHODS

Airflow control can be classified in two main groups.

| **Device adds no momentum in tunnel axis:** | **Device adds momentum in tunnel axis:** |
|---|---|
| Air extraction | Jet fans |
| Undirected fresh air injection | Directed fresh air injection (e.g. by Saccardo nozzles) |
| Air curtain | Distributed directed injection of supply air |
| Mechanical curtain | |

## 3. EXPERIMENT

### 3.1. Objective

At present, a number of road tunnels in Switzerland as well as in other countries are subject to critical review in respect of fulfilling the requirements given by the valid guidelines and state of the art of tunnel ventilation design.

In some cases, the existent ventilation system is oversized by far considering the normal operation due to the massively decreased vehicle emissions. On the other hand, the same systems often lack the capabilities to effectively cater for tunnel fires and the related smoke extraction requirements.

It is intended to refurbish certain tunnels that are equipped with transversal ventilation systems to adapt them to the present requirements.

In some cases, there is no space available for the installation of jet-fans in the existing structures. So the choice is either to carry out massive construction works in order to provide a number of jet-fan niches throughout the tunnel or to search for alternative solutions.

Being a very suitable object to investigate this kind of alternative solutions, the Crapteig Tunnel in Switzerland has been chosen for experiments.

### 3.2. Description of the Tunnel

The Crapteig Tunnel has been inaugurated 1997. It is 2.2 km long and located on the A13 San Bernardino transit highway between the villages Thusis and Andeer.

The cross section area is relatively large due to 2 lanes going upward from North to South and one lane going downward at a slope of approximately 6.5%. Due to the steep slope, the Crapteig Tunnel is subjected to a discernable stack effect while at the same time the portals are also subjected to wind forces.

At present, the ventilation system comprises distributed fresh air supply for normal operation and distributed smoke extraction in the case of a tunnel fire.

Two ventilation stations close to the portals each accommodate a supply air fan and a dual mode fan. The latter can be used for supply as well as for extraction purposes and comprises variable pitch. All fans are equipped with variable speed drives which makes this system very versatile and a good basis for experiments.

Isolated by a false ceiling against the driving space, two ducts extend throughout the tunnel in the ceiling.

One of the ducts is used for air supply only. It is connected to a supply air fan at each end and connected to the driving space by secondary ducts, injecting the fresh air above the road level perpendicular to the tunnel axis.

The second duct is divided in two sections by means of an isolation damper in the middle of the tunnel, resulting in two ventilation sections, each connected to its own dual mode supply/extraction fan. Via slots in the ceiling (see

Figure 1), air can be either injected with a momentum to the tunnel axis, or extracted. Linear, distributed extraction was originally intended for fire ventilation.

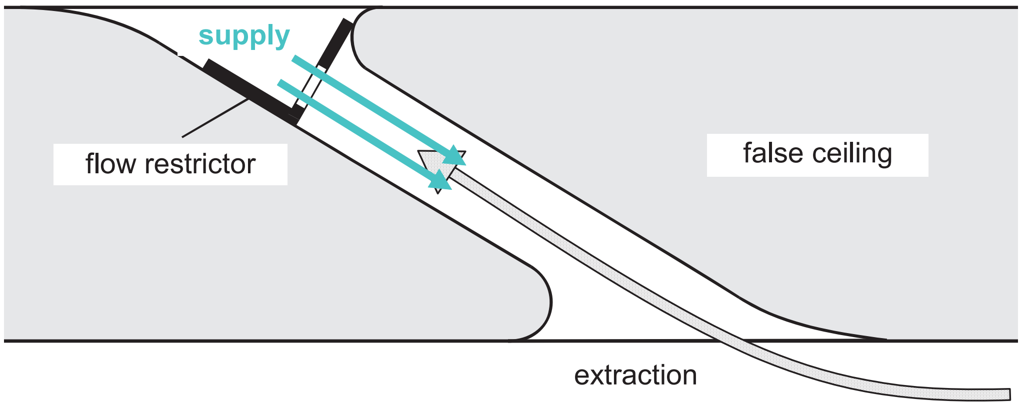



**Figure 1**: Sketch of openings for distributed injection/extraction in false ceiling

As a unique feature, the tunnel comprises large, hydraulically operated flap gates at each end of the extraction duct. This facility was intended for the concentrated removal of waste tunnel air before reaching the portals. Measured against the axis of the tunnel, the flaps are inclined at an angle of 18.5° in the open position, see Figure 1.

**Figure 2:** Flap gate, used for portal air extraction, open position

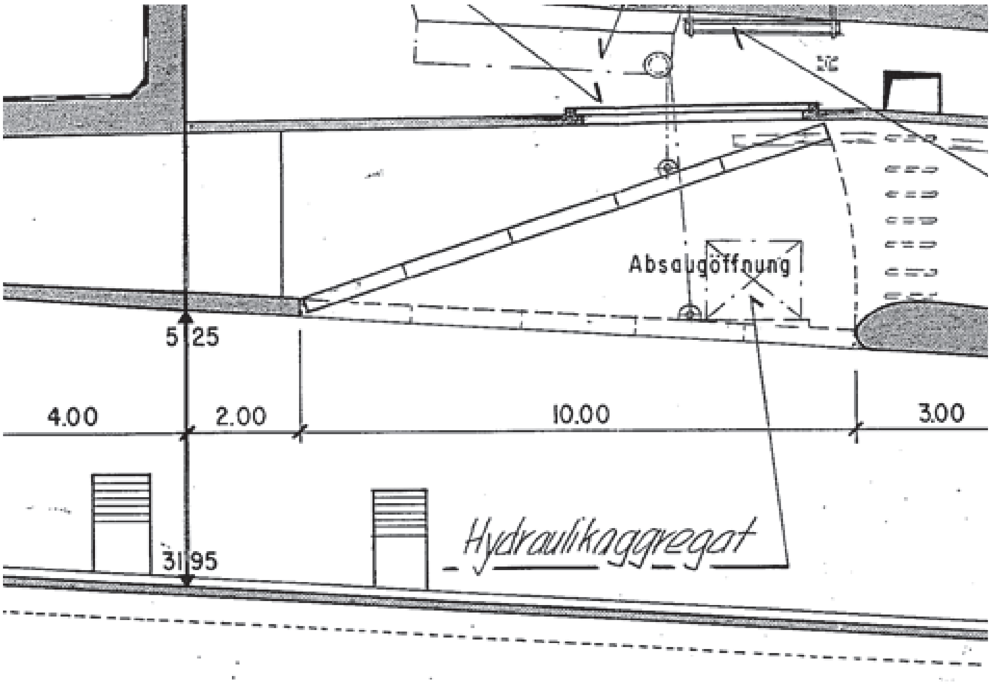



**Figure 3:** Longitudinal section of flap gate

### 3.3. Experimental Setup

Using the equipment of the Crapteig tunnel, various operation modes of air injection could be tested. By operating the dual mode fan in supply mode, both, point injection through the flap gate or distributed, directed injection through the slots in the ceiling could be applied. The large opening of the existing flap gate also provided space to install a provisional Saccardo nozzle mock-up.

The flap gates are situated approximately 150 m from the portals. At 2 locations, the air velocity in the tunnel is measured by a group of 3 ultrasonic anemometers. The readings of those instruments have been calibrated against results of a grid measurement according to ISO 5802.

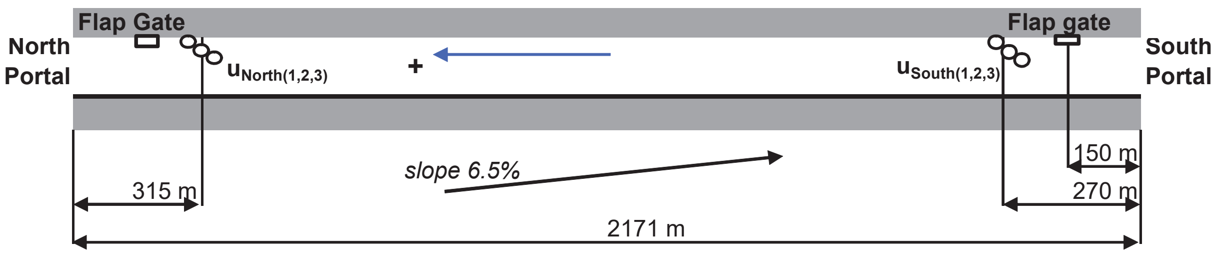



**Figure 4:** Location of anemometers and flap gates

As the fans are not equipped with volume flow meters, this value has been determined by evaluation of the fan curves at the operating points for the different modes.

To introduce disadvantageous propulsion forces, a mobile jet fan was used, see Figure 5.

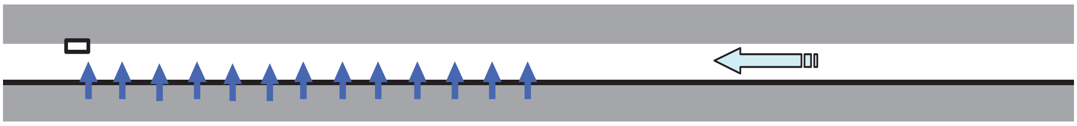
**Figure 5:** Mobile jet fan

**Figure 6:** Setup of Saccardo nozzle mock-up

### 3.4. Configurations

The following scenarios have been investigated:

- Deceleration of flow by distributed and undirected fresh air supply in one of two supply air sections



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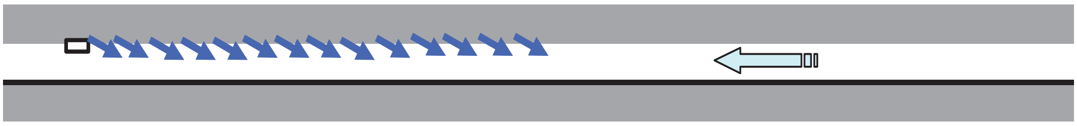

- Deceleration and reversal of flow by point injection of fresh air (open flap gate)

- Acceleration of flow by point injection of fresh air (Saccardo Nozzle)

- Deceleration and reversal of flow by point injection of fresh air (Saccardo Nozzle)

## 3.5. Calculations

The following dimensions and specifications of the tunnel and of the propulsion devices have been used in the 1-D calculations:

Dimensions of tunnel:

| | |
|---|---|
| L (length of tunnel): | 2171 m |
| A (cross section area): | 60 $m^2$ |
| $D_H$ (hydr. diameter): | 7 m |
| (friction coefficient): | 0.03 |

Distributed injection – undirected:

| | |
|---|---|
| Angle of injection: | 90° |
| Volume flow rate: | 100 $m^3/s$ |
| Length of supply air section: | 1050 m |
| Exit velocity: | estimated 20 m/s |

Distributed injection – directed:

| | |
|---|---|
| Angle of injection: | ca. 30° |
| Volume flow rate: | 95 $m^3/s$ |
| Length of supply air section: | 1050 m |
| Exit velocity: | est. 20 m/s |

Saccardo-Nozzle:

| | |
|---|---|
| Angle of injection: | 15° |
| Exit velocity: | 25 m/s |
| Nozzle exit area: | 4.65 x 0.65 m |
| Volume flow rate: | 80 $m^3/s$ |

Not calculated:
Single point injection through flap gate

| | |
|---|---|
| Angle of injection: (estimation) | ca. 20° |
| Volume flow rate: | 100 $m^3/s$ |
| Cross section area of jet: | unknown |
| Exit velocity: | unknown |

## 3.6. Results

The following full scale measurement has been used to validate the 1-D model.

**Deceleration and reversal of air flow in the tunnel by means of the Saccardo nozzle.**

At the start of this experiment, a steady air flow from North to South in the order of 1.5 m/s was present due to a temperature difference between the warmer tunnel and the ambient air. Using a reasonably estimated momentum exchange coefficient of $k_{MX}$ = 0.8, a good agreement between measurements and calculation results can be observed (see Figure 7).

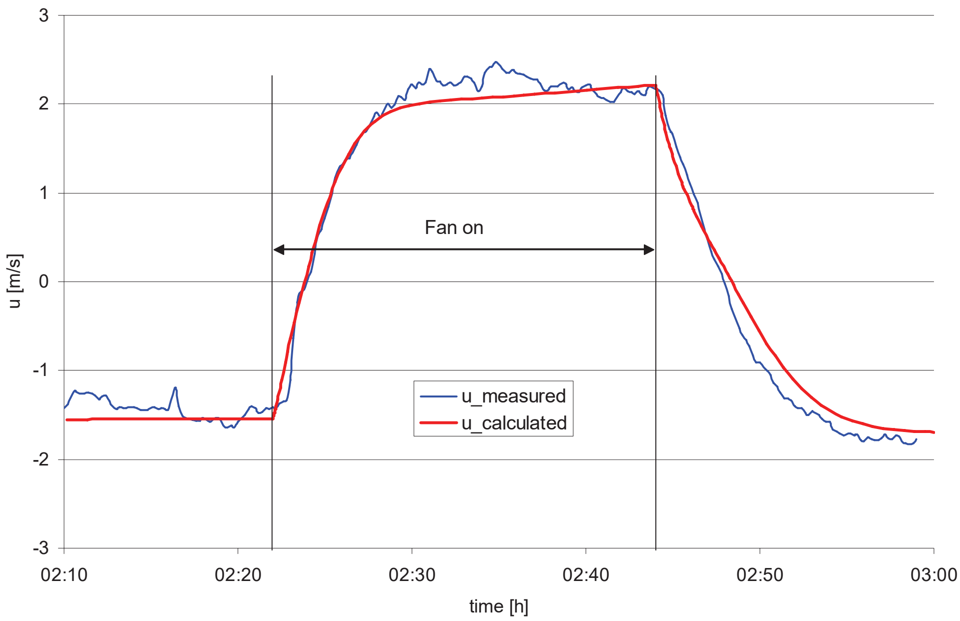


**Figure 7:** Air velocity in tunnel during operation of Saccardo nozzle

**Comparison of propulsion methods**

For comparison purposes, the effect of the injection of air by four different propulsion methods has been calculated. In each case, the nozzle air volume flow and a nozzle exit velocity has been applied according to the specifications above.

Alternatively, a group of 3 jet-fans or one Saccardo-nozzle is located in a distance of 100 m to the entry portal. Beginning from that location, a section of distributed supply air injection extends over a length of 1000 m into the tunnel. The resulting velocity is calculated for the exiting air at the end of the tunnel.

Possible delays due to the inertia effects in the supply air ducts or caused by the start-up of the connected fans have not been considered in this stage of the model.

In Figure 8, the unsteady behaviour of the air flow in the downstream half of the tunnel is illustrated. Figure 9 shows the distribution of the static pressure along the axis of the tunnel tube for the equilibrium steady state.

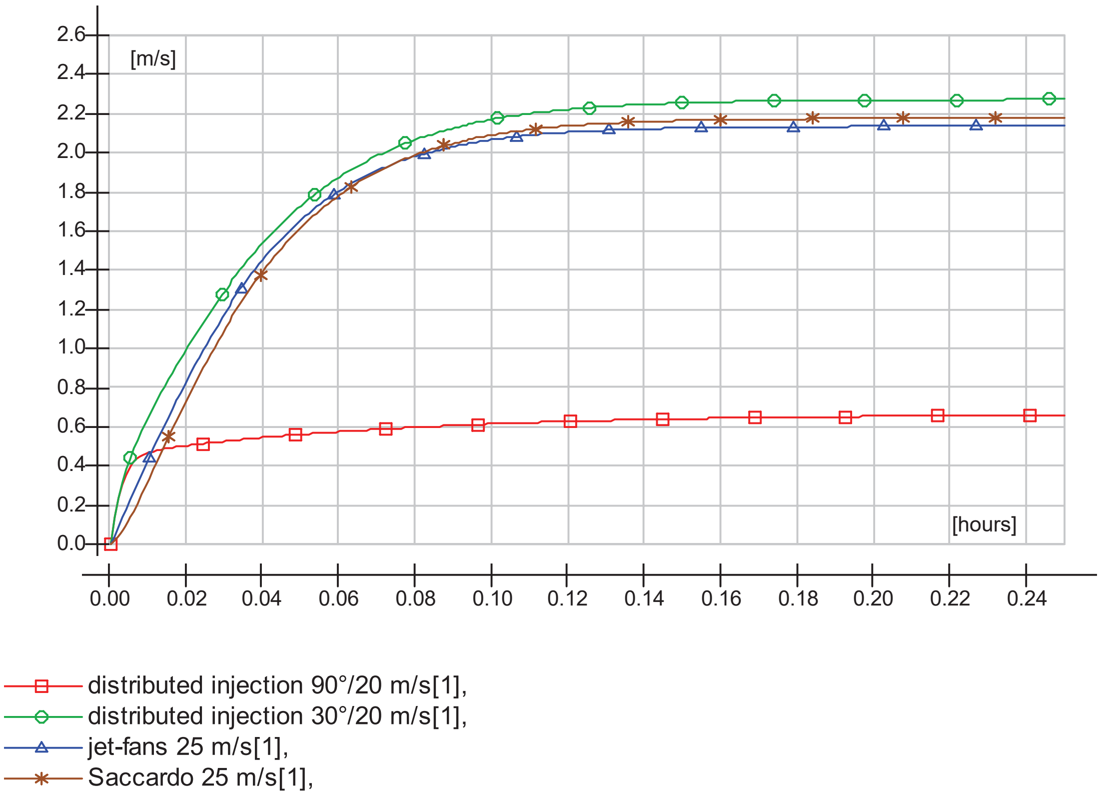


**Figure 8:** Calculated air velocities in tunnel for the four different propulsion methods

In Figure 10, the effect of the different propulsion methods is shown as it was recorded in the full scale experiment.

As the exit velocities of the distributed air injection are not known exactly, this result is of qualitative use only.

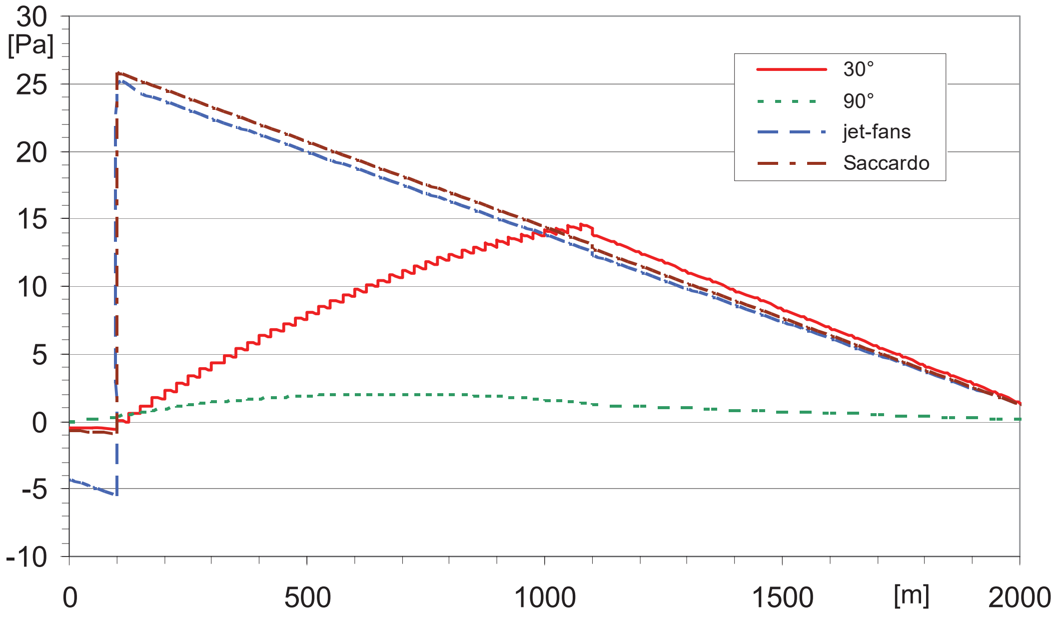


**Figure 9:** Distribution of static pressure along tunnel axis

As to be expected according to the calculations, the effect of the distributed and directed air injection is of the same order as the effect of the Saccardo nozzle. The effect of the undirected injection is much less effective.

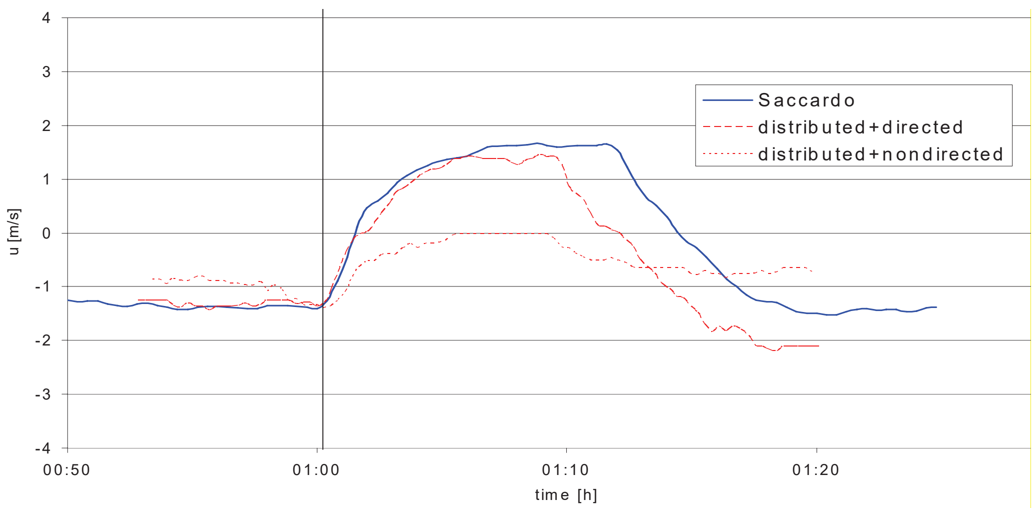


**Figure 10:** Qualitative comparison of propulsion methods in full scale experiment

Even though the distributed injection may be effective for the control of longitudinal airflow, it is not applicable for fire ventilation as long as the section with openings extends far into the tunnel. The injection of air into a possible smoke layer would further enhance the smoke procurement. The Swiss guideline does not allow the injection of air through the ceiling for this reason.

## 4. CONCLUSIONS

The following conclusions can be drawn:

i. For the control of airflow in a tunnel, only methods that directly inject momentum into the flow are useful without restrictions. Primarily these methods are either jet fans or Saccardo nozzles.

ii. Only in long tunnels with powerful transversal ventilations systems and various dedicated ventilation sections can the distributed air injection be used to control the longitudinal airflow efficiently.

iii. For most applications, jet fans are useful due to their efficiency, simple installation and easily achievable redundancy.

iv. Saccardo nozzles may be considered where space requirements, serviceability without restriction and protection from corrosion are important.

v. Especially for the refurbishment of tunnels with existing ventilation stations, Saccardo nozzles may be a cost-effective solution.

vi. The application of directed air injection at fixed points is a suitable option for the control of longitudinal air flow in case of tunnel fires. Although the energy efficiency is clearly smaller than in a jet-fan setup, this does not matter much because it is operated only during the hopefully rare case of a tunnel fire.

vii. Apparently, the propulsion effect of an injection of fresh air through an adapted Saccardo nozzle, through the geometrically much less defined damper opening and through distributed openings for directed injection is of nearly equal order, considering the velocity if the air flow at the opposite end of the tunnel.

viii. The one dimensional simulation technique is an adequate instrument to predict the dynamic performance of control of longitudinal ventilation in road tunnels. However the efficiency coefficients for the propulsion devices may have to take into account the flow regime, i.e. whether the jet is directed against the main airflow or not.

## 5. ACKNOWLEDGEMENTS

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